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How quickly they forget: The relationship between forgetting and working memory performance

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Running Head: Forgetting and working memory span in children

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Abstract

This study examined the contribution of individual differences in rate of forgetting to variation in working memory performance in children. 112 children (mean age 9 years 4 months) completed two tasks designed to measure forgetting, as well as measures of working memory, processing efficiency, and short-term storage ability. Individual differences in forgetting rate accounted for unique variance in working memory performance over and above variance explained by measures of processing efficiency and storage ability. In addition, the nature of the variation in forgetting was more consistent with a non-executive forgetting parameter than an executive ability associated with resistance to interference. These findings indicate that individual differences in the rate at which information is lost from memory is an important constraint on children's working memory performance which has implications for current models of working memory that do not incorporate such a factor.

Keywords: Working memory, Forgetting rate, Executive ability

How quickly they forget: The relationship between forgetting and working memory span performance

The construct of working memory is of considerable interest to researchers because of the well-established relationship between performance on tasks designed to assess the capacity of working memory and cognitive skills such as reasoning ability (Kyllonen & Christal, 1990), language comprehension (Daneman & Merikle, 1996), reading and mathematics ability (Hitch, Towse, & Hutton, 2001), and general fluid intelligence (Oberauer, Schulze, Wilhelm, & Süß, 2005). Recent research has explored this relationship both directly, by examining the factors that influence the predictive relationship between working memory and cognition (Friedman & Miyake, 2004; Lépine, Barrouillet, & Camos, 2005; Unsworth & Engle, 2005, 2007a), and also indirectly, by identifying the factors that constrain working memory performance, and thus, are likely to be important for higher-level cognitive skills (Barrouillet, Portrat, & Camos, 2011; Bayliss, Jarrold, Gunn, & Baddeley, 2003; Kane, Bleckley, Conway, & Engle, 2001; Unsworth & Engle, 2007b). This has led to the development of a number of theories about the nature of working memory and its relationship to higher-order cognition.

Many of these theories have postulated the involvement of a central executive or attentional control system in working memory (Cowan, 1999; Engle, Kane, & Tuholski, 1999). For example, Engle and colleagues (Engle, Kane, et al., 1999; Kane et al., 2001) argued that working memory consists of a short-term storage component and a controlled attention component, which they likened to the central executive in Baddeley and Hitch's (1974) original working memory model. The controlled attention component was thought to be a limited-capacity mechanism responsible for focused, goal directed processing in the face of interference or distraction. Engle and colleagues (Engle, Kane, et al., 1999; Kane et al., 2001) argued that individual differences in the capacity for controlled attention were responsible for the strong relationship between working memory performance and higher-level cognition. In support of this, Engle, Tuholski, Laughlin, and Conway (1999) showed that residual variance from a working memory variable that remained once variance common to short-term memory was removed, was significantly correlated with a fluid intelligence variable (see also Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Towse & Houston-Price, 2001). They suggested that this residual variance in working memory performance reflected the controlled attention or executive component of working memory (though see Colom, Rebollo, Abad, & Shih, 2006). Bayliss et al. (2003) have also shown that residual variance in working memory span performance that remains once variance associated with the processing and storage operations involved in the working memory span task is removed, reliably predicts reading and mathematics performance in both children and adults (see also Towse & Houston-Price, 2001). These findings indicate that this residual variance does not simply reflect measurement error (see also Jarrold & Bayliss, 2007), but instead, indexes an additional factor that is important for higher-level cognitive performance. In line with the suggestion of Engle and colleagues, Bayliss et al. (2003) attributed this residual variance to an executive ability that is involved in working memory span performance (see also Bunting, 2006; Conway et al., 2002; Towse & Houston-Price, 2001; Unsworth & Spillers, 2010).

However, the interpretation of this residual variance as ‘executive’ has been purely speculative and to date, there have been few direct attempts to specify exactly what it is that this residual variance captures. One possibility is that it does indeed reflect domain-general executive-attention as Engle and his colleagues have suggested. In support of this, Kane et al. (2004) derived a single domain-general "executive-attention" factor and two domain-specific storage factors from a battery of verbal and visuo-spatial working memory and short-term memory tasks, and showed that the executive-attention factor was closely associated with a fluid intelligence variable. The executive-attention variable elicited high loadings from the verbal and visuo-spatial working memory tasks and lower loadings from the STM tasks providing support for the claim that it represented a domain-general factor associated with higher-level cognition. Kane et al. (2004) argued that the variance captured by this factor reflected the ability to maintain information in an active state, particularly in the presence of interference and/or competition between response alternatives that must be resolved. The finding that individuals with low working memory capacity suffer from proactive interference to a greater extent than individuals with high working memory capacity when asked to recall a series of lists with overlapping memory items is consistent with this executive attention account (Kane & Engle, 2000). More recent versions of this account have argued that the extent to which executive attention is required to maintain and/or recover access to memoranda, is determined by the amount of conflict, distraction or interference present in the task context (Kane, Conway, Hambrick, & Engle, 2007). Thus, the residual variance captured by working memory tasks could be thought of as reflecting the executive attention resources required to prevent the deleterious effects of interference on working memory performance.

A potentially related suggestion is that the residual variance in working memory performance is associated with individual differences in the degree to which information is lost during the working memory task due to forgetting. Forgetting from short-term/working memory has typically been attributed to one of two main causes, namely, a passive process of decay over time (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet, De Paepe, & Langerock, 2012; Ricker & Cowan, 2010), or some form of interference that could be either retroactive, as in interference from subsequent events within the task (Lewandowsky, Duncan, & Brown, 2004; Lewandowsky, Geiger, Morrell, & Oberauer, 2010), or proactive, as in interference that builds up between memoranda across successive trials (Bunting, 2006; Keppel & Underwood, 1962). Regardless of which of these factors is responsible for forgetting from working memory, there is some evidence to suggest that individuals may indeed vary in the rate or degree to which they forget information. For example, Cowan and colleagues (Cowan, Nugent, Elliott, & Saults, 2000; Saults & Cowan, 1996) have shown age-related differences in the rate of forgetting of auditory memory. Using an ignored speech paradigm, Cowan et al. (2000) found that younger children showed more rapid forgetting of unattended information across a filled retention interval than older children. Crucially, however, this difference was limited to the last item in the unattended list, with no such age differences found for earlier serial positions or for the attended speech condition. Cowan et al. argued that the final serial position was free from retroactive interference from other list items and so, age differences in degree of forgetting localised to this serial position were best accounted for in terms of a developmental increase in the retention of auditory sensory memory. Moreover, this aspect of memory development was argued to be independent of attention. In adults, Unsworth, Brewer and Spillers (2011) have also shown that individual differences in working memory capacity are associated with differences in forgetting. In their study, high working memory capacity participants showed better memory for paired-associates than low working memory participants across a range of retention intervals, but performed comparably when tested immediately after presentation of a given pair. Unsworth et al. argued that variation in working memory capacity could be explained in terms of differences in controlled retrieval processes that act to limit the size of the search set at retrieval, and ultimately, influence the amount of information that individuals forget across a retention interval. Thus, there is some evidence that individuals may vary in the rate at which they lose information from memory.

One might ask whether this variation in forgetting rate is simply a reflection of variation in the opportunity to engage in refreshing or reactivation of memory traces that in turn follows from differences in the speed with which individuals complete processing operations. Barrouillet and colleagues (2004, 2007; Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; see also Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005; Jarrold & Bayliss, 2007) argued that engaging in the processing activity of the working memory span task prevents individuals from carrying out active maintenance of the to-be-remembered items (cf. Barrouillet & Camos, 2001; Towse, Hitch, & Hutton, 2002). As a consequence of this, the speed with which individuals complete the processing operations leads to variation in the time during which forgetting can occur whilst maintenance activities are prevented. Evidence to support this suggestion comes from a recent study by Barrouillet et al. (2012), who showed that lengthening the duration of the processing activity whilst maintaining a constant time between the end of each processing activity and presentation of the subsequent storage item (i.e., the time available for restoring or refreshing the memory trace) resulted in poorer memory performance, consistent with the idea that longer processing leads to greater forgetting (see also, Bayliss et al., 2005, who showed that age-related changes in a speed of processing variable accounted for unique variance in working memory span performance). In addition, by systematically manipulating the amount of time during which children were engaged in processing and the time they had available for refreshing memory items, Barrouillet et al. (2009) were able to show that the slope relating the time available for refreshing memory items with working memory span performance was steeper in older relative to younger children. They argued that this provided evidence of a faster rate of reactivation in older children (see also Bayliss et al., 2005; Gaillard, Barrouillet, Jarrold, & Camos, 2011; Tam, Jarrold, Baddeley, & Sabatos DeVito, 2010).

However, variation in the time available for forgetting and the time available for refreshing cannot explain the residual variance found by Bayliss et al. (2003), as the variation in working memory span associated with individual differences in processing speed and storage ability was statistically removed in this earlier work. Similarly, Ricker and Cowan (2010) argue that models that propose an equilibrium between forgetting and reactivation processes cannot explain the pattern of forgetting observed in their study. They presented adult participants with either three unconventional visual characters or six English letters in a memory array, followed by a retention interval of either 1500, 3000, or 6000ms. The retention interval was either unfilled (i.e., a no load condition) or filled with a distractor activity that varied in difficulty (i.e., in Experiment 1, repeating digits vs. performing subtraction). For the English letter condition, no forgetting across retention intervals was evident for the no load condition, in which participants were free to use maintenance strategies, whereas significant forgetting was observed across retention intervals when maintenance strategies were blocked by the inclusion of a distractor activity. Crucially, in the unconventional character condition, while introducing a distractor activity significantly impaired performance in the load conditions relative to the no load condition, the rate of forgetting that was observed across the measured retention intervals was equivalent for all conditions. Ricker and Cowan (2010) suggested that for certain stimuli—in this case, the unconventional visual stimuli—some features of the stimulus are inevitably lost over time and cannot be refreshed via attentional or rehearsal mechanisms. This finding is significant as it demonstrates a time-based loss of information that is independent of any cognitive load. In relation to the Bayliss et al. (2003) study, this leads to the possibility that individuals may vary in the extent to which they forget information whilst engaged in the processing activity of a working memory task, and that this is what the residual variance in working memory span performance represents. To our knowledge, the extent to which individual differences in the rate with which individuals forget information contributes to working memory performance, independently of storage and processing ability, has never been studied before.

The first aim of this study was, therefore, to examine whether residual variance in working memory span performance, that remains once variance associated with the processing and storage operations has been removed, is related to individual differences in rate of forgetting. Evidence to support this claim would have important implications for current theories of working memory, most of which do not incorporate a forgetting rate factor independent of other storage and processing abilities. If an independent contribution of forgetting rate to working memory span performance can be established, the next logical question is what underlies this variation in forgetting rate. The literature offers a number of possible answers to this question that could be broadly classified into either controlled, strategic, executive-type factors on the one hand, or more basic, automatic, non-executive factors on the other. For example, Engle and colleagues would suggest that variation in rate of forgetting is mediated by an executive ability associated with resisting interference, either from subsequent events that occur within the trial (i.e., distractor activity) or from similar memory items presented in previous trials (i.e., proactive interference) (see also, Unsworth et al., 2011). However, other possible causes of variation in forgetting rate include individual differences in more basic parameters such as decay or interference effects that are not executive in nature. It has certainly been suggested that individuals may vary in the *rate* at which information decays from memory during processing (Barrouillet et al., 2009; Cowan, Saults, & Nugent, 1997; Hitch et al., 2001; Oberauer & Kliegl, 2001; Portrat, Camos, & Barrouillet, 2009), and the rate of such trace decay could vary between individuals independently of any attentional control processes that might serve to offset it. Similarly, it is plausible that individuals may differ in their susceptibility to interference effects, such as feature overwriting (e.g., Nairne, 1990), that occur simply by virtue of representations sharing overlapping features. The second aim of this research was, therefore, to systematically manipulate the factors expected to contribute to the rate of forgetting to examine which, if any, of these possibilities best accounts for the residual variation in working memory span performance.

To address these goals, two interpolated tasks were designed to measure rate of forgetting in children. Children were the chosen sample for this study for two reasons. First, there is considerable variation in working memory and executive abilities in a sample of children, partly because these processes are still undergoing development. As a result, the range of abilities evident in a sample of children is usually larger than in a typical sample of undergraduate students, which makes a child sample ideal for individual differences studies. Second, in our previous work, we have successfully developed a method for fractionating the sources of variance contributing to working memory performance in children (Bayliss et al., 2003, 2005) and we employed the same approach here. This study extends that work by including additional measures of forgetting. In these forgetting rate tasks, participants were presented with three to-be-remembered words and were then required to complete a continuous processing activity for either a short or long duration, before recalling the to-be-remembered items. These tasks were designed to measure the amount of information that people forget when maintenance activities are prevented by a continuous processing activity. It was expected that recall performance would be poorer in the long duration conditions relative to the short duration conditions as maintenance activities would be prevented for longer, thus allowing more forgetting to occur (cf. Brown, 1958; Peterson & Peterson, 1959; Towse et al., 2002). If residual variation in working memory span performance reflects individual differences in forgetting, then we would expect to see a relationship between the residual variance derived from working memory span tasks and performance on the two forgetting tasks.

To address the second aim of this study, and to characterise the nature of any variation in forgetting rates that might be related to residual variance in working memory, the amount of interference encountered in the two forgetting tasks was manipulated by a) systematically varying the interpolated processing activity involved in each task, and b) deriving measures of proactive interference effects by contrasting performance on the first half versus the second half of trials. The relationship between each of these measures and residual variation in working memory span was then examined. If the residual variation in working memory span reflects variation in an executive factor associated with resistance to interference, then we would expect to see a stronger association between the residual variance and performance on the forgetting task that involved a greater degree of interference, whether that be from increased interference from the interpolated distractor activity or increased interference from previous trials (i.e., proactive interference). In contrast, if the residual variance best reflects a basic forgetting rate parameter, then the association between the residual variance and the measures of forgetting should be comparable.

Method

Participants

A total of 117 children participated in the study with full parental consent. Of these children, the data from four children were excluded because they did not complete all the tasks in the battery due to absence on the final days of testing or moving out of the area. The data from one additional child were excluded because the school identified the child as having difficulties associated with an Autistic Spectrum Disorder. The mean age of the remaining 112 participants was 9 years 4 months (range 8;9 to 10;2).

Design

Each child completed the battery of tasks in four separate sessions on different days. In the first session, each child completed the object speed task followed by the object working memory span task. The order of presentation of the forgetting tasks was counterbalanced across participants in the second and third sessions. Half of the children completed the colour forgetting task and the digit span task in the second session, and the object forgetting task and the counting speed task in the third session. For the remaining participants, the order of presentation of these sessions was reversed. In the fourth session, all children completed the counting working memory span task followed by the word span task.

Tasks and Procedure

All tasks were presented on a 15-inch Elo USB Touchscreen controlled by a laptop computer.

Forgetting tasks

Each participant completed two forgetting tasks; the colour forgetting task and the object forgetting task. In both tasks, a trial commenced with the sequential presentation of three to-be-remembered words in black 48-point Helvetica font on a white background. Each word was presented for 1 second followed by a 300ms inter-stimulus interval during which the screen was blank. To counteract any difficulties with word reading, each word was simultaneously presented auditorily in a female voice. Following the presentation of the last word, the display screen changed to signal the beginning of the continuous processing activity. The display screen used for the processing activity consisted of nine different coloured squares (red, blue, green, yellow, pink, orange, purple, white, & brown) measuring 35mm each side, presented in a random arrangement on a grey background.

In the colour forgetting task, the processing activity involved the auditory presentation of colour names in a male voice. The children were required to locate the appropriately coloured square and touch it as quickly as they could. In the object forgetting task, the processing activity involved the auditory presentation of object names that reliably cued one of the nine colours (i.e., banana = yellow). The children were asked to think of the colour typically associated with the object and then touch the appropriately coloured square on the screen as quickly as possible. As soon as the child responded by touching the screen, the next processing item was presented. To prevent articulatory rehearsal, the children were also required to name the colour of each square as they touched it. Once the processing activity had been performed for a specified duration, the children were presented with a blank screen and simultaneously heard a brief tone to signal the end of the trial, and were then asked to recall the three to-be-remembered words in correct serial order.

Each forgetting task consisted of 16 trials, half of which were presented with a short duration processing activity of 4000ms (short), and half of which were presented with a long duration processing activity of 8000ms (long). However, as the continuous processing activity did not end until the child made a response to the final processing item, these processing durations varied slightly (mean duration = 4020.39 and 7950.64ms in the short and long conditions respectively). The trials were counterbalanced so that there were two short duration and two long duration processing activities presented within each consecutive set of four trials. The order of presentation of the trials was the same for each participant. An additional four trials were presented at the start of each task as practice.

A pool of 60 single syllable concrete nouns were selected from the MRC Psycholinguistic Database on the basis that they were high frequency (Kucera-Francis written frequency > 20), had low age of acquisition (AOA < 500), high concreteness (Conc > 400), and high imageability (Imag > 400) ratings (see Appendix). In addition, all words had a frequency rating from the Celex database of greater than 20. These words were used to form two pools of 30 words that were closely matched on the variables above (Celex, $t(58) = .52$; K-F Freq, $t(58) = .19$; AOA, $t(58) = -.01$; Conc, $t(58) = -.02$; Imag, $t(58) = .37$; $p > .10$ in all cases). One of these pools of words was assigned to the short duration condition and the other was assigned to the long duration condition. The same words were used in both the colour and the object forgetting tasks but the order of presentation of these words varied.

To manipulate the amount of interference encountered in the two forgetting tasks, the items used for the processing activity of each task varied (cf. Conlin, Gathercole, & Adams, 2005). The items used in the processing activity of the colour forgetting task were the nine colour names already described above, which were expected to be relatively distinct from the storage items. In contrast, the processing items used in the object forgetting task consisted of 69 object names, which were expected to interfere with the retention of the storage items to a greater extent as both sets of items were concrete nouns. The object names were selected from those used in Bayliss et al. (2005) on the basis that they reliably cued one of the nine colours presented in the display screen (i.e., snow = white). In the colour forgetting task, a non-exhaustive list of colour names was created by randomising consecutive lists of the nine colour names. Similarly, for the object forgetting task, a non-exhaustive list of object names was created by randomising consecutive lists of the 69 object names. The same list of colour names and list of object names was then presented to all participants. However, as the presentation of the processing items was determined by the speed of each child's responses, some children were able to complete more of these processing items within each processing activity than others. The timing and accuracy of responses to each processing item was recorded by the computer and participants' recall responses were recorded by the experimenter. Items were scored correct if they were recalled in the correct serial position and the overall proportion correct was calculated for each duration condition within each task.

Working memory span tasks

Two working memory span tasks were completed by each participant; the object working memory span task and the counting working memory span task. Both tasks involved a series of processing and storage episodes. In the object working memory span task, participants were presented with a display screen similar to that used in the processing activity of the forgetting tasks. Nine different coloured squares measuring 35mm each side were presented on a grey background, with the numbers 1 to 9 presented in the centre of the squares in black. At the start of each processing episode, participants were presented with a verbal object name that reliably cued one of the nine colours, and were required to think of the colour typically associated with that object and then touch the appropriately coloured square on the screen as quickly as possible. As they touched the square, participants were required to verbalise the number that was in the centre of the square, and remember that number for recall at the end of the trial. Following a set number of processing and storage episodes, participants were asked to verbally recall the numbers that they had named during the trial in correct serial order. Trials increased from 2 to a maximum of 6 processing and storage episodes with 4 trials at each span length. Testing continued until a child failed all four trials at a given span length. An additional three trials at span length 2 were given at the start of the task as practice.

The 86 processing items used in the object working memory span task were taken from Bayliss et al. (2003). All items were recorded in a male voice and adjusted to 1 second in length by adding silence to the start of the shorter items. To control for differences in processing difficulty across span lengths, trials were organised so that the mean reaction time to items within each span length was equated across span lengths, $F(4,220) = .57$, $p > .10$, based on response times to each item taken from previous work (Bayliss et al., 2003). In addition, each coloured square in the display was cued approximately equally often in each serial position, and each of the digits 1-9 was cued approximately equally often in each serial position.

The counting span task was adapted from one used by Towse, Hitch, and Hutton (1998). The display screen consisted of an array of blue squares and red triangles presented in a random arrangement in a white rectangle measuring 144mm by 108mm that was centred on the screen. To the left and right of this rectangle, two smaller rectangles measuring 47mm by 65mm were displayed with the words ‘Odd’ and ‘Even’ presented in the centre of the left and right rectangles respectively. At the onset of each processing and storage episode, participants were presented with one of these screens and were required to count the number of blue squares, pointing to each square as they counted it, and to decide whether the total number of squares was an odd or even number. They then responded by touching the odd or even rectangle on the screen, at which point, the squares and triangles disappeared and a digit between 1 and 9 was presented in the centre of the screen in black. Participants were asked to name the digit and remember it for later recall. After a series of processing and storage episodes, the children were asked to recall the digits that they had named in correct serial order. As with the object working memory span task, trials increased from 2 to a maximum of 6 processing and storage episodes in length with four trials at each span length and three additional trials presented at the start of the task as practice. Testing was terminated when a child failed all four trials at a given span length.

86 different counting arrays were created with 20 arrays each consisting of 2, 3, 4, or 5 blue squares presented amongst 8 red triangles, plus an additional 6 arrays that were created for practice. An equal number of each of these array sizes were presented at each span length, and the number of times an odd counting array was followed by an odd or even digit and vice versa was approximately equal. In addition, each digit was presented approximately equally often in each serial position.

The timing of the processing and storage episodes in both tasks was carefully controlled. Participants were given 4000ms to respond to the processing episode of each task (i.e., to find the appropriately coloured square or to count the blue squares and make an odd or even judgement). If a participant responded within this time, the storage item was presented and remained on the screen until a total of 5000ms had elapsed, at which point, the next processing episode was presented. If a child failed to respond within 4000ms, the storage item was automatically presented for a further 1000ms before the presentation of the next processing episode. The accuracy and timing of participant's responses to the processing items was recorded by the computer and participant's recall responses were recorded by the experimenter at the time of testing. Trials were scored correct if items were recalled in the correct serial position and span scores were calculated by averaging the last four correctly recalled trials (i.e., two trials correctly recalled at 2, one at 3 and one at 4 would give a span score of 2.75).

Storage tasks

Each participant completed two storage tasks; a digit span task (which corresponded to the storage requirements of the working memory span tasks), and a word span task. In the digit span task, participants were visually presented with digits between 1 and 9 in the centre of the screen in black. The digits were presented for 1000ms followed briefly by a blank screen before the presentation of the next digit. Participants were asked to name each digit as it was presented and then recall the digits in correct serial order at the end of the trial. Trials increased from 3 to a maximum of 8 digits in length with 4 trials at each length. An additional two trials were given at the start of the task as practice. Each digit was cued approximately equally often in each serial position. Testing continued until a child failed all 4 trials at a given span length. Span scores were calculated as an average of the last four correctly recalled trials.

In the word span task, participants were visually presented with words in black 48-point Helvetica font on a white background. Each word was presented for 1000ms followed by a blank screen for 300ms and then the next word. As with the forgetting tasks, each word was simultaneously presented auditorily in a female voice. Trials increased from 2 to 6 words in length with four trials at each span length and an additional two trials given at the start of the task as practice. The 84 words used in the word span task consisted of the 60 words used in the forgetting tasks plus an additional 24 words that also met the criteria described above. Trials were organised so that any semantic associations between the words within each trial were avoided as much as possible. Testing continued until a child failed all four trials at a given span length and span scores were calculated in the same way as in the digit span task.

Processing efficiency tasks

Independent measures of processing efficiency were taken using an object association task, and a counting speed task. In the object association task, participants were presented with a display screen similar to that used in the working memory span tasks but without any digits on the screen. To provide a measure of each child's colour knowledge and also as a check for colour blindness, participants were first presented with each of the nine colour names auditorily and were required to touch the appropriately coloured square as quickly as possible. Once a response was made, the screen was cleared and a start button was presented. Children were asked to touch the start button when they were ready to proceed to the next trial. Following this, 36 of the object names used in the working memory span tasks (4 of each colour) were presented auditorily and participants were asked to think of the colour typically associated with each object and then touch the appropriately coloured square as quickly as possible. This corresponded to the processing activity of the working memory span task, but without any storage requirements. Participants were then presented with each of the colour names again and were asked to touch the correct square as quickly as possible.

In the counting speed task, participants were presented with 36 of the counting arrays (9 of each array size) used in the counting working memory span task and were asked to count the number of blue squares, ignoring the red triangles, and decide if the number was odd or even. They were then required to indicate their response by touching either the 'Odd' or 'Even' button as quickly as possible. If they responded correctly, they heard a 'boing' noise, the screen was cleared, and a start button was presented to enable them to continue to the next trial. If they responded incorrectly, they heard a low pitch tone and the count array remained on the screen until they had responded correctly. Accuracy and response times were recorded by the computer. Instructions and practice examples were given prior to the task using a card displaying a count array.

Results

Preliminary Analysis

Response times in the processing efficiency tasks were trimmed to remove any extraneous responses. Initially, any response times greater than 10 seconds were removed. The remaining response times were then Windsorized, in line with the recommendations of Ratcliff (1993), by replacing any response times more than 2.5 standard deviations above the mean for each individual item with the cut-off value for that item. Participants' response times to the 36 object names in the object association task were then averaged to provide a measure of each individual's object processing efficiency. In the counting speed task, response times were averaged across the 36 counting arrays.

To ensure that the fixed list length of three items presented in the forgetting rate tasks was within the capacity of each participant, an estimate of immediate recall performance was calculated from the four trials presented at list length 3 as part of the word span task (i.e., a baseline measure of immediate recall performance at 0ms). Only those participants who showed perfect recall on these trials were included in the subsequent analyses (n=88)[1]. This has the added advantage of making sure that estimates of forgetting were derived relative to the same baseline level of immediate recall across participants (see below). Of course, individuals who are performing at ceiling on the baseline measure may have immediate recall capacities that extend beyond three items, and so even at this level of performance, there may be differences in the strength of encoding of the memory items across individuals. However, we would assume these to be collinear with individual differences in storage capacity which will be controlled for in the subsequent analyses. Descriptive statistics for all measures are presented in Table 1.

Forgetting Tasks

Recall scores on the two forgetting tasks were subjected to a 2x2 repeated measures analysis of variance, with task (colour, object) and duration (short, long) as the factors. This revealed a significant effect of task, $F(1, 87) = 60.03$, $p < .001$, $\eta_p^2 = .41$, reflecting poorer performance on the object task relative to the colour task. There was also a significant effect of duration, $F(1, 87) = 215.12$, $p < .001$, $\eta_p^2 = .71$, indicating that recall performance was better in the short conditions than the long conditions, and no significant interaction between task and duration, $F(1, 87) = 0.05$, *p* = .82, η_p^2 = .00. Thus, recall performance in the colour and object conditions was not differentially affected by the increase in retention duration from 4000 to 8000ms.

As the duration of the processing activity involved in the colour and object forgetting tasks varied slightly, depending on the point at which participants made their final response within the prescribed time window, it is possible that the task effect may have been inflated by differences in the actual retention interval in each task. To examine this, a second analysis was conducted in which slope and intercept values were derived for each participant, based on their average processing durations in the short and long conditions of both tasks respectively. Processing durations were taken as the time between the onset of the processing activity and the child's response on the final processing item immediately prior to recall. The intercept values for the colour and object forgetting tasks were then subjected to a paired-sample t-test, which was significant, $t(87) = 2.43$, $p = .02$, indicating that even when any differences in processing duration were taken into account, recall performance in the object forgetting task was still worse than in the colour forgetting task. In addition, analysis of the slope values derived for each task revealed a non-significant difference, $t(87) = -0.28$, $p = .78$, confirming the previous finding that there was no difference between the two tasks in the rate of forgetting between 4000 and 8000ms.

To provide a measure of the degree or rate of forgetting across each task, two proportional difference scores were obtained for each task by calculating the proportion decrease in recall performance from a baseline measure (calculated as the proportion correct on the four trials presented at list length 3 as part of the word span task) to performance at 4000ms (0-4000) and the proportion decrease in recall performance from performance at 4000ms to performance at 8000ms (4000-8000)[2]. Analysis of the estimates of forgetting (i.e., the proportional difference scores) revealed a significant difference between the 0-4000ms estimates from the colour and object tasks (*M* = .38 & .50 respectively), $t(87) = -5.83$, $p <. 001$, and between the 4000-8000ms estimates from the colour and object tasks (*M* = .35 & .45 respectively), $t(86) = 2.35$, $p = .02$.

To provide an estimate of the amount of forgetting experienced due to the build-up of proactive interference, two additional scores were obtained for each forgetting task by calculating the proportion correct on the first half of trials and proportion correct on the second half of trials. Any evidence of greater forgetting in the second as opposed to the first half of trials would be consistent with the suggestion that proactive interference builds up over trials and is maximal at the end of the task. Consistent with this idea, a 2x2 repeated measures analysis of variance, with task (colour, object) and trials (first half, second half) as the factors revealed a significant effect of trials, $F(1, 87) = 12.14$, $p < .01$, $\eta_p^2 = .12$, with poorer performance in the second half of trials (*M* = 0.42, *SD* = 0.17) relative to the first half of trials (*M* = 0.47, *SD* = 0.17). There was also a significant effect of task, $F(1, 87) = 82.80$, $p < .01$, $\eta_p^2 = .49$, but no significant interaction between task and trials, $F(1, 87) = 0.51$, $p = .48$, $\eta_p^2 = .01$.

Is performance on the forgetting tasks related to residual variance in working memory span performance?

To examine this initial question, we first explored the pattern of correlations between the estimates of forgetting for each task, the working memory span measures, the storage measures and the measures of processing speed (Table 2). The correlations presented in Table 2 show that the two 0-4000ms forgetting measures were closely related to each other, indicating that there was some shared variance between these two variables. These two forgetting measures were also associated with the working memory span measures, suggesting that there may be a relationship between these indices of performance. The two 4000-8000ms forgetting measures were significantly correlated with each other, but showed no reliable associations with the two 0-4000ms forgetting measures or the two working memory span measures. Finally, the working memory span measures showed significant correlations with the independent measures of storage ability and the independent measures of processing efficiency.

These relationships were further examined by an exploratory factor analysis performed using a maximum likelihood extraction on the data from the four forgetting measures, the two working memory span tasks, the two storage tasks, and the two measures of processing efficiency. This revealed a four-factor structure that accounted for 71.01% of the total variance. The four-factor solution was rotated using a direct oblimin procedure to facilitate the interpretation of the factors. The loadings from the pattern matrix are presented in Table 3. The two 0-4000ms forgetting measures loaded on the first factor, suggesting that this factor corresponded to a forgetting rate factor associated with the first 4000ms period of the forgetting tasks. The second factor appeared to represent a forgetting rate factor associated with the 4000-8000ms period, with loadings from the two 4000-8000ms forgetting measures, and the third factor corresponded to a storage-related factor with loadings from the two working memory span measures and the two measures of storage ability. The fourth factor appeared to represent a processing speed factor with loadings from the two measures of processing efficiency and a smaller loading from the counting working memory span task. The 0-4000ms forgetting rate factor showed some association with the storage-related factor (.27) and the processing efficiency factor (-.35), which were themselves correlated (-.45). However, the 4000-8000ms forgetting rate factor showed little association with any of the other three factors (-.05, .05 and .05, respectively). The fact that the 0-4000 and the 4000-8000ms forgetting measures loaded on different factors suggests that they are not measuring the same constructs. Moreover, given that the 4000-8000ms forgetting rate factor showed no association with the other factors, which was consistent with the correlational analysis, this factor was not included in any further analyses.

To examine the extent to which the 0-4000ms forgetting rate measures were associated with residual variance in working memory span performance, that remained once variation associated with processing efficiency and storage ability was removed, a structural equation modelling (SEM) analysis was performed. In this model, we specified direct paths from three latent variables representing Forgetting Rates (with loadings from the two 0-4000ms forgetting rate measures), Storage Ability (with loadings from the two storage tasks), and Processing Speed (with loadings from the two processing efficiency tasks) respectively, to a fourth latent variable representing Working Memory (with loadings from the two working memory span tasks). Model fit was assessed using a combination of fit statistics. These indicated that the model provided a good fit to the data. More specifically, the χ^2 test was non-significant, χ^2 (14) = 15.45, p = .35, indicating that the estimated covariance matrix was not significantly different from the observed covariance matrix, and the root mean square error of approximation (RMSEA), which provides an estimate of the discrepancy between the estimated and observed covariance matrices, was less than .05 (RMSEA = .03). In addition, the comparative fit index (CFI) and the goodness-of-fit index (GFI), which compare the fit of the specified model to a baseline independence model, were both above .95 (CFI = .99 and GFI = .96). Parameter estimates for this model are presented in Figure 1. As shown in the Figure, both

Storage Ability and Processing Speed significantly predicted Working Memory ($p < .05$ in both cases), thus replicating the findings of Bayliss et al. (2003) and showing that processing efficiency and storage ability are important and distinguishable constraints on children's working memory span performance. Importantly, the path from the Forgetting Rate variable to the Working Memory variable was also significant ($p < .05$), indicating that individual differences in forgetting rate are related to the residual variation in working memory span performance that remains once variation associated with the processing and storage operations is removed.

What is the nature of this residual variation in working memory span performance?

To explore the nature of this residual variation in working memory span performance in more detail, a series of hierarchical regression analyses were conducted. The analysis of the forgetting tasks reported above suggested that, as expected, the object forgetting task involved more interference than the colour forgetting task, leading to more forgetting. Similarly, performance on the second half of trials was worse than performance on the first half of trials, consistent with the suggestion that proactive interference constrained performance on the second half of each task. That being the case, if the residual variance in working memory span performance reflects an executive factor associated with maintaining information in the face of interference from the processing activity, then we might expect performance on the object forgetting task to be more closely associated with the residual variance than the colour forgetting task, and consequently, account for more variance in working memory span performance. A similar prediction can be made in relation to the build-up of proactive interference, with performance on the second half of trials being expected to account for unique variance over and above variance accounted for by performance on the first half of trials.

To examine the first of these predictions, the variance associated with the independent measures of storage ability and processing efficiency was removed by entering the digit span measure and the task-specific measure of processing speed on the first step. Then, the order of entry of the 0-4000ms forgetting measures from the colour and object tasks was systematically varied to identify the unique contribution associated with each when entered on the last step. The results of this analysis are presented in Table 4. The analyses revealed that the object forgetting measure did not contribute any additional variance to the object working memory span task, $F(1, 83) = 0.03$, $p = .86$, or the counting working memory span task, $F(1, 83) = 1.48$, $p = .23$, over and above the significant contributions of the colour forgetting measure. However, the object forgetting measure did contribute significant variance when entered on the first step of the analysis for the counting working memory span task, $F(1, 84) = 9.06$, $p < .01$. This indicates that most of the variance (i.e., approximately 85-100%) that the object forgetting measure contributed to working memory span performance was shared with the colour forgetting measure.

To determine whether high proactive interference forgetting rate trials were better predictors of residual variance in working memory performance than low proactive interference forgetting rate trials, a similar analysis was performed with the measures of performance taken from the first half of trials (Low PI) and the second half of trials (High PI) for each forgetting task. The order of entry of these measures was varied to identify the unique contribution of each when entered on the last step. The results of this analysis are presented in Table 5. The analysis revealed that the High PI variables accounted for significant variance when entered on the first step of the analysis for the counting working memory span task, $F(2, 83) = 7.57$, $p < .01$, and marginally significant variance when entered on the first step of the analysis for the object working memory span task, $F(2, 83) = 2.46$, $p = .09$. However, the High PI variables did not account for any unique variance over and above the Low PI variables for either the object working memory span task, $F(2, 81) = 0.32$, $p = .73$, or the counting working memory span task, $F(2, 81) = 1.32$, $p = .27$. Again, this indicates that most of the variance that the High PI variables contributed to working memory span performance was shared with the low PI variables (i.e., approximately 80%).

Discussion

This study was designed to a) examine whether individual differences in forgetting rate contribute unique variance to children's working memory span performance, and b) examine potential sources of this variation by systematically manipulating factors thought to contribute to individual differences in the rate of forgetting. In line with expectations, recall performance on the forgetting tasks declined with increasing retention duration; recall was poorer in the long relative to the short duration conditions (cf. Towse et al., 2002). This indicates that the forgetting tasks, developed for use in this study, were successful at inducing forgetting (see also, Ricker & Cowan, 2010). In addition, the factor analysis revealed that the measures of forgetting taken from these tasks were separable from measures of both storage ability and processing speed. Consistent with this, individual differences in forgetting accounted for unique variance in working memory span performance, over and above variation associated with the processing and storage operations involved in each working memory span task. The fact that the two forgetting rate estimates taken from the long retention intervals did not correlate with working memory span performance as strongly as the estimates taken from the short retention intervals (see Table 2) suggests that individual differences in forgetting rate may be best captured within the early phase of the forgetting function. This may be because the greatest loss of information appeared to occur during the first four seconds of each task (i.e., given that all participants had perfect recall on the baseline measure; see Table 1) and highlights the importance of measuring forgetting across different retention intervals.

The findings from this study replicate and advance previous research that has identified unique contributions of processing efficiency and storage ability to working memory span performance (i.e., Bayliss et al., 2003, 2005) by demonstrating that the residual variance that remains once variance associated with these component processes is removed is more than just measurement error, and, instead, is meaningful variation that can be captured and described. This finding is important because it provides evidence that working memory span performance can be decomposed into a number of separable factors, and suggests that one of these factors is associated with the rate at which individuals lose information from memory. Crucially, this rate of information loss is separable from the rate at which individuals perform the processing components of the working memory tasks, and so individual differences in forgetting rate cannot be reduced to variation in basic speed of processing.

The results of the factor analysis provide further support for this claim and are important for two reasons. First, they replicate Bayliss and colleagues' previous finding of separate processing and storage factors (Bayliss et al., 2005). Coupled with the finding that processing efficiency and storage ability each contribute unique variance to working memory span performance, these results again suggest that both factors need to be incorporated into any account of working memory performance.

Second, the finding that the forgetting measures and the working memory span tasks load on separate factors is intriguing given that both the forgetting tasks and working memory span tasks could be thought to rely on the same underlying mechanisms (Halford, Maybery, O'Hare, & Grant, 1994; though see Jarrold, Tam, Baddeley, & Harvey, 2011) and might have been expected to load together. The fact that they load on separate factors indicates that the contribution of the forgetting measures to working memory span performance cannot be explained purely in terms of shared methodological variance. Indeed, Jarrold et al. (2011) showed that the working memory span performance of a sample of adults differed from their performance on Brown-Peterson tasks, tasks that were similar in structure to the forgetting tasks used in the current study, in terms of both overall mean performance and the types of errors made. Intrusion errors from prior lists occurred significantly more often in the Brown-Peterson tasks which is consistent with the view that proactive interference, due to response competition between plausible response alternatives, was operating in these tasks. In addition, they argued that this forgetting due to across-trial interference was independent of the interference occurring between storage and processing items within each trial of the working memory span tasks, which they instead attributed to an overlap of representational features (cf. Nairne, 1990).

Taken together, the current findings indicate that children’s working memory span performance can be decomposed into at least three separable factors that individuals may vary on, namely, their storage ability, their general speed of processing, and the rate at which they forget information. The unique contribution of processing speed is consistent with models of working memory span performance in which individual or developmental differences in processing efficiency lead to variation in the time during which maintenance activities are prevented and forgetting can occur (i.e., Barrouillet et al., 2004, 2007, 2009, 2012; Bayliss et al., 2005; see also Towse et al., 1998). Likewise, the unique contribution of storage ability is consistent with models in which individual or developmental differences in reactivation rate determine the amount of information that can be successfully maintained or refreshed in any unoccupied time windows that occur during the working memory span task (Barrouillet et al., 2009; Bayliss et al., 2005). Consistent with this argument, recent studies have shown that older children are able to take greater advantage of any free time during a working memory span task (Barrouillet et al., 2009; Gaillard et al., 2011; Tam et al., 2010). However, the novelty of the current study is that we have identified a third constraint on working memory performance that is separate from the constraints imposed by limitations in processing speed and storage ability. This constraint is associated with an individual's susceptibility to forgetting, that is, individual variation in the rate or degree to which information is lost from memory when any form of maintenance activities are prevented. For example, one could imagine two children who have similar processing speeds but vary in terms of their rate of forgetting. In the working memory span paradigm, both children would complete the processing activity of the task in a similar time, meaning that the time available for forgetting was comparable. However, the child with the faster rate of forgetting would experience a greater loss of information during that time relative to the other child, and consequently, their working memory performance would be poorer. While previous researchers have made suggestions along these lines (Barrouillet et al., 2009; Cowan et al., 1997; Hitch et al., 2001; Oberauer & Kliegl, 2001; Portrat et al., 2009), this is the first study to show evidence consistent with such a claim.

Moreover, the results of this study go some way towards specifying the source of the residual variation in working memory span performance that is associated with forgetting. As expected, recall performance was poorer in the object relative to the colour forgetting task, suggesting that participants did experience more interference in the object task, where the processing and storage items were both concrete nouns, than in the colour task, where the processing items were relatively distinct from the storage items (cf. Conlin & Gathercole, 2006; Jarrold et al., 2011). In addition, consistent with the substantial evidence for proactive interference effects in Brown-Peterson paradigms (Crowder, 1989; Keppel & Underwood, 1962), performance on the second half of trials was poorer than performance on the first half of trials in the forgetting tasks. Given these findings, if variation in forgetting is due to individual differences in the ability to resist interference, either within or across trials, then the contribution from trials involving more of these types of interference should be particularly predictive of working memory performance. However, the object forgetting measure did not contribute any unique variance to working memory span performance over and above that contributed by the colour forgetting measure. Instead, between 85-100% of the variation in working memory span performance accounted for by the object forgetting measure was shared with the colour forgetting measure. This finding provides little support for the claim that one of the important contributions to variation in working memory span performance is from individual differences in an executive ability associated with resisting interference from competing response alternatives (see also Oberauer, 2009). Similarly, the High PI measures derived from each forgetting task did not contribute any unique variance to working memory span performance over and above the Low PI measures. Again, approximately 80% of the variation in working memory span performance accounted for by the High PI measures was shared with the Low PI measures. Taken together, these results do not appear to be consistent with the controlled attention model of Engle and colleagues (i.e., Engle, Kane, et al., 1999; Kane et al., 2001). In this model, resisting interference from response competition is a central function of the controlled attention or 'executive' component of working memory with greater competition within a task context requiring more executive attention resources for successful performance (Kane et al., 2007). The object forgetting task used in this study was explicitly designed to capture individual variation in the ability to resist interference from response competition. The fact that performance on this task did not contribute unique variance to working memory performance, nor a measure of performance taken under conditions of high proactive interference, presents a challenge for the influential and widely-held view that individual differences in the ability to resist interference moderates the extent of forgetting from working memory.

This begs the question of what is driving the variation in forgetting captured by the tasks developed in this study. One possibility is that individuals may vary in the rate at which information decays from memory during processing (Cowan et al., 1997; Hitch et al., 2001; Oberauer & Kliegl, 2001). Indeed, the finding of Cowan et al. (2000) that younger children showed a greater loss of auditory sensory information over time than older children is consistent with this idea. Cowan et al. (2000) argued for the recognition of attention-independent aspects of memory that change with development. The variation in forgetting rates captured in the present study may indeed fall into that category and could potentially be accommodated by the Time-Based Resource Sharing (TBRS) model of Barrouillet and colleagues (Barrouillet et al., 2004; 2009). In this model, processing and maintenance rely on a single limited attentional resource. Items that fall out of the focus of attention suffer time-related decay but can be refreshed by a rapid switching of attention to the memory item. Thus, processing efficiency and rate of reactivation are important factors in this model. Barrouillet et al. (2009) also suggested that speed of decay may be another potential factor contributing to developmental differences in working memory, but as yet, have not explicitly included such a factor in the TBRS model. The recent study of Ricker and Cowan (2010) also highlights the need to incorporate a constraint on working memory associated with loss of information over time, in addition to any effects due to the prevention of attentional refreshing or reactivation. The results of the present study are consistent with these ideas and suggest that a modification of the TBRS model along these lines may be warranted.

An alternative possibility is that the variation captured by the forgetting tasks does reflect an interference mechanism, but one that is not related to executive functioning. Oberauer (2009) examined the mechanisms of interference involved in a working memory span task by varying the similarity of the processing and memory items in various ways. While high phonological and semantic similarity between processing and memory items did not impair recall performance relative to low similarity, high phoneme overlap and a fast pace of presentation did. Oberauer (2009) argued that these findings provided evidence for at least two mechanisms in the working memory span task, one associated with the distraction of attention from maintenance activities, which we assume is captured in our study by individual differences in processing speed, and an interference mechanism associated with feature overwriting (see also Jarrold et al., 2011; Oberauer, Farrell, Jarrold, Pasiecznik, & Greaves, 2011; Saito & Miyake, 2004). As the processing and memory items used in the forgetting tasks in the current study were all words, they are likely to share numerous phonological features, and so, it is plausible that performance on the forgetting tasks reflects the degree of interference caused by feature overwriting. Thus, the variation captured by the forgetting tasks in this study could readily be explained by individual differences in a basic memory decay parameter or a form of interference associated with an individual's susceptibility to feature overlap between the processing and memory items.

Having said this, numerous studies have provided evidence of a relationship between individual differences in working memory and the ability to resist interference (Kane & Engle, 2000; Unsworth, 2010; see also Bunting, 2006, & Gray, Chabris, & Braver, 2003, who have shown a relationship between performance on trials subject to interference from recent stimulus items and general fluid intelligence), and the suggestion in the current study that the residual variance in working memory span performance may reflect a non-executive factor appears to be at odds with this earlier work. Three points are relevant to this issue. The first is to note that we have not explained all of the variation in working memory span performance, and so, we are not claiming that there is no executive contribution to working memory performance. It is always possible that a different measure of executive functioning may explain some of this residual variance. Secondly, our study was conducted with a sample of children and it is possible that the nature of the residual variance changes across development. Even though our previous work has shown remarkably similar patterns of relationships across both child and adult samples (e.g., Bayliss et al., 2003), a replication of this study with an adult sample would be a worthy avenue for future research. Finally, it is likely that the storage and processing operations that contribute to working memory performance require executive processes to some extent (see Ang & Lee, 2008, & Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001, for evidence of this in relation to spatial short-term memory) and so, executive abilities may well contribute to individual differences in working memory. However, what we have shown is that individual differences in forgetting rates do account for significant variance in working memory span performance, independently of processing and storage, and that in contrast to what is typically assumed with regards to residual variance in working memory, this variation in forgetting rates may not be mediated by an executive ability. A second point to make is that one could argue that performance on both forgetting tasks requires some resistance to interference. Although the executive attention account of working memory would presumably predict that the object forgetting task involves more response competition than the colour task, if the colour forgetting task does involve a degree of competition between response alternatives, then performance on this task will still be affected by the ability to resist interference. It then follows that individual differences in an executive ability associated with resisting interference will be captured by measures taken from the colour forgetting rate task as well. The fact that the object task did not contribute any unique variance in working memory performance over and above the colour task could then be explained by assuming that individuals are resisting interference to the best of their ability on the colour task. Consequently, while adding extra interference in the object task does produce a drop in memory performance overall, it would not necessarily influence the pattern of individual differences captured. Such a suggestion would leave open the possibility that the variance captured by the forgetting tasks is executive in nature, but clearly depends on the assumption that individual differences in the ability to resist interference are maximised in the colour forgetting task and that increasing the executive demands of a task does not expand these differences any further. The challenge that these data pose to proponents of an executive view of forgetting is whether this is a plausible suggestion and whether the variance captured by the forgetting tasks, which is reliable and predictive of working memory, can be convincingly shown to be executive in nature.

In conclusion, the results of this study suggest that children's working memory performance is best understood in terms of a number of separate abilities. That is, children may vary in terms of their processing speed, their storage ability, and the extent to which they suffer forgetting. The key finding of the current study is that each of these components can be reliably measured, and in doing so, we have begun to demystify the nature of the 'residual' variation in working memory span performance that has commonly been attributed to an executive ability associated with controlling attention and resisting interference. In contrast to this view, the findings from the present study suggest that at least some of the residual variance in working memory span performance may be best conceptualised as a non-executive parameter associated with forgetting. While the cause of this forgetting could readily be attributed to either time-based decay or interference due to feature overwriting, crucially, neither of these mechanisms necessitate any executive involvement. Whether any other executive abilities can explain some of the residual variance in working memory performance remains to be seen, but irrespective of this, current models of working memory that attribute residual variance in working memory to an executive ability will need to carefully consider what it is that they are referring to as 'executive' and whether the balance of evidence supports such a claim.

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Footnotes

1. Analyses performed with the sample as a whole produced the same pattern of results. Specifically, the analysis of performance on the forgetting rate tasks showed significant effects of task, $F(1,111) = 59.24$, $p < .001$, and duration, $F(1,111) = 253.04$, $p < .001$, and no interaction between task and duration, $F(1,111) = 1.66$, $p = .20$. Analysis of the first half of trials compared to the last half also revealed significant effects of trials, $F(1, 111) = 15.30$, $p < .01$, and task, $F(1,111) = 74.60$, $p < .01$, and no interaction between task and trials, $F < 1$. An exploratory factor analysis showed a similar four factor structure and, importantly, a SEM analysis showed that the model presented in Figure 1 also provided a good fit to the data from the larger sample, χ^2 (14) = 12.52, $p = .57$, with the Storage Ability, Processing Speed and Forgetting Rate variables all significantly predicting the Working Memory Variable (all $p \leq .05$). Finally, the 0-4000ms object forgetting measure did not contribute any additional variance to the object or counting working memory span tasks (all $p > .10$) over and above the significant contribution of the colour forgetting measure, but did contribute significant variance when entered on the first step of the analyses ($F(1,108) = 5.65$ and 10.29, $p < .05$ respectively). The only difference identified was that the unique contribution of the Low PI measures to the counting working memory span task was significant. Data are available from the first author on request.
2. A 4000-8000ms forgetting rate estimate could not be calculated for one child as they failed to recall any items correctly in the short condition of the object

forgetting rate task. Thus, all analyses involving this variable are based on 87 participants.

Figure Caption

Figure 1. Structural equation model and parameter estimates for Forgetting Rate, Storage Ability and Processing Speed predicting Working Memory. The numbers next to the single-headed arrows leading from the latent variables to the observed variables are the standardized factor loadings and the single-headed arrows leading from the Forgetting Rate, Storage Ability and Processing Speed variables to the Working Memory variable are standardized regression weights. The values next to the curved double-headed arrows represent correlations, and the values next to the small single-headed arrows leading to the observed variables reflect the residual variance or proportion of unexplained variance for each task.

Table 1

Summary of Descriptive Statistics for all Measures (Proportion Correct for Forgetting Rate Tasks; Span Scores for Working Memory and Storage Tasks; RTs in ms for Processing Efficiency Tasks).

Measure	Mean	SD	Min.	Max.	Reliability	Skew	Kurtosis
Forgetting Rate Tasks							
Colour Short	.62	.20	.25	1.00	.64	-0.11	-1.06
Colour Long	.39	.19	.00	.92	.68	0.54	0.21
Object Short	.50	.20	.00	.96	.68	-0.22	-0.06
Object Long	.27	.18	.00	.79	.64	0.49	-0.40
Working Memory Span							
Object	4.32	0.77	2.25	5.75	.74	-0.43	-0.29
Counting	4.23	0.92	2.00	6.00	.76	-0.32	-0.44
Storage Tasks							
Digit Span	4.66	0.62	3.25	7.00	.72	0.97	2.08
Word Span	4.08	0.53	3.25	5.50	.69	0.52	-0.14

Processing Efficiency							
Object	2680.34	425.24	1636.57	3476.79	.83	-0.12	-0.64
Counting	2130.47	511.12	1179.63	3558.51	.92	0.77	0.50

n = 88

Table 2

Matrix of Pearson Correlation Coefficients for all Measures (n = 88)

Target Measures	1	2	3	4	5	6	7	8	9	10
1. Colour FR 0-4000	___									
2. Colour FR 4000-8000	-.20	___								
3. Object FR 0-4000	**.53**	.15	___							
4. Object FR 4000-8000[a]	.08	**.27**	-.06	___						
5. Object WM Span	**-.41**	.13	**-.24**	.08	___					
6. Counting WM Span	**-.50**	-.05	**-.38**	.07	**.57**	___				
7. Digit Span	-.13	-.05	-.12	.03	**.41**	**.37**	___			
8. Word Span	**-.29**	-.21	**-.35**	.00	**.45**	**.45**	**.54**	___		
9. Object Speed	**.23**	.05	**.31**	-.01	**-.27**	**-.42**	**-.22**	**-.24**	___	
10. Counting Speed	**.32**	.20	**.24**	.08	**-.29**	**-.49**	**-.23**	**-.25**	**.54**	___

Note. Correlations significant at $p < .05$ or above are presented in bold.

[a]$n = 87$ for correlations involving this variable.

Table 3

Factor Loadings for the Exploratory Factor Analysis with Oblique Rotation

	Factor			
Measures	1	2	3	4
Colour FR 0-4000	**-.985**	-.112	.016	.049
Colour FR 0-8000	.242	**.976**	-.252	.034
Object FR 0-4000	**-.477**	.135	-.233	.019
Object FR 0-8000	-.125	**.320**	.122	.021
Object WM Span	.212	.212	**.494**	-.141
Counting WM Span	.250	.042	**.388**	**-.363**
Digit Span	-.071	.030	**.669**	-.086
Word Span	.110	-.123	**.754**	.042
Object Speed	.038	-.050	-.042	**.646**
Counting Speed	-.008	.107	.076	**.860**

Table 4

Unique Contributions of the Colour and Object Forgetting Rate Measures to each Working Memory Span Task

Object Working Memory Span				
Step	Variable(s)	ΔR^2	Variable(s)	ΔR^2
1	Object Speed, Digit Span	.20**	Object Speed, Digit Span	.20**
2	0-4000 Colour FR	.11**	0-4000 Object FR	.02
3	0-4000 Object FR	.00	0-4000 Colour FR	.09**
Counting Working Memory Span				
Step	Variable(s)	ΔR^2	Variable(s)	ΔR^2
1	Counting Speed, Digit Span	.31**	Counting Speed, Digit Span	.31**
2	0-4000 Colour FR	.12**	0-4000 Object FR	.07**
3	0-4000 Object FR	.01	0-4000 Colour FR	.06**

Note. The proportion of the variation that the object forgetting measure contributed to working memory performance that was also shared with the colour forgetting measure was estimated by subtracting the unique variance accounted for by the object forgetting measure on the last step of the regression analyses from the total variance accounted for by the object forgetting measure on the second step of the regression analyses, and then dividing the result by the total variance accounted for by the object forgetting measure on the second step of the regression analyses. For example, for the counting working memory span task above, the resultant equation using three decimal places would be: .067-.010 = .057; (.057/.067) x 100 = 85%. A similar procedure was used to calculate the proportion of shared variance for the PI measures shown in Table 5.

*p<.05. **p<.01.

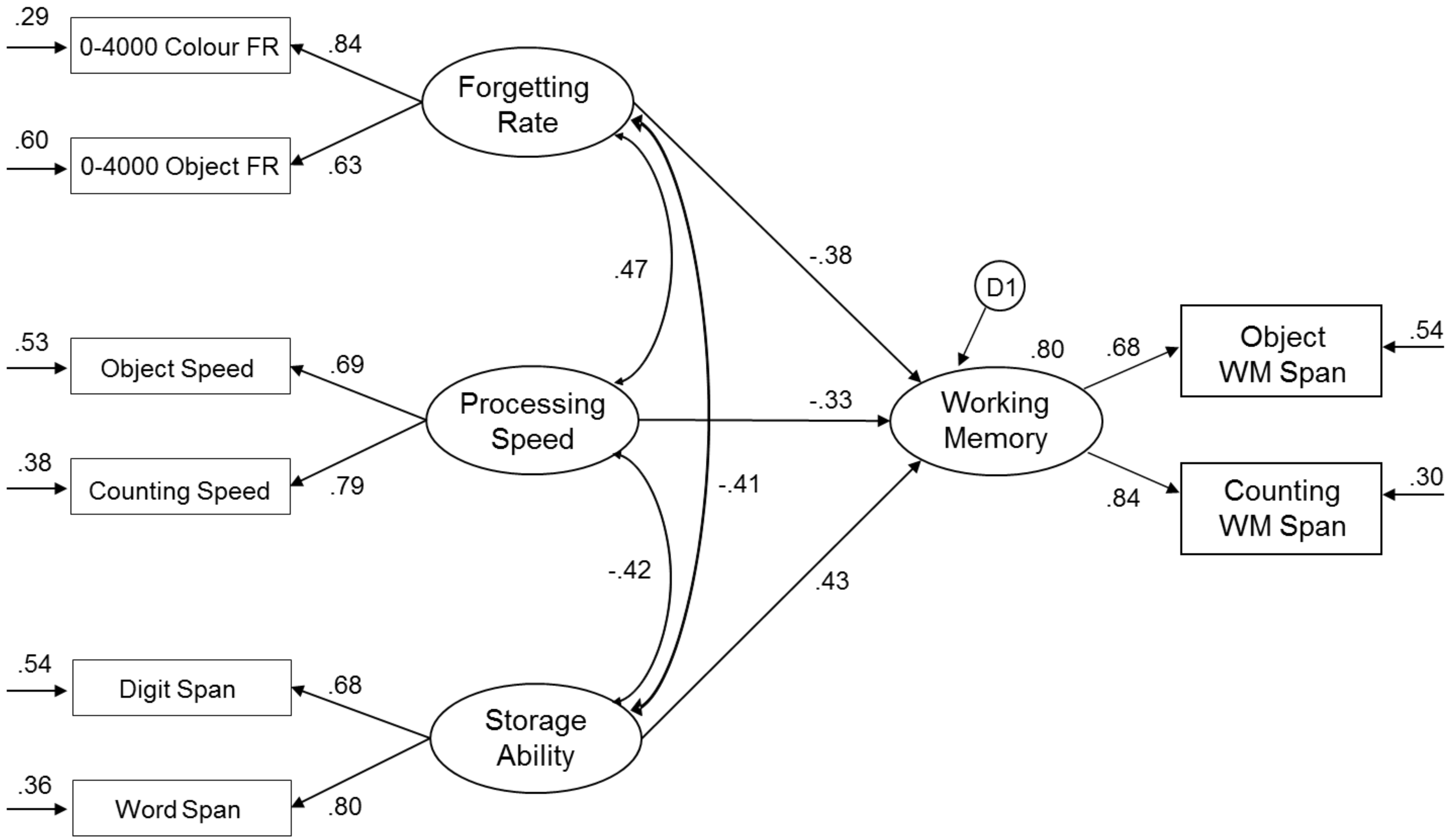
Table 5

Unique Contributions of the Proactive Interference Measures to each Working Memory Span Task

Step	Variable(s)	ΔR^2	Variable(s)	ΔR^2
Object Working Memory Span				
1	Object Speed, Digit Span	.20**	Object Speed, Digit Span	.20**
2	Low PI Colour, Low PI Object	.06*	High PI Colour, Hi PI Object	.05
3	High PI Colour, Hi PI Object	.01	Low PI Colour, Low PI Object	.02
Counting Working Memory Span				
Step	Variable(s)	ΔR^2	Variable(s)	ΔR^2
1	Counting Speed, Digit Span	.31**	Counting Speed, Digit Span	.31**
2	Low PI Colour, Low PI Object	.11**	High PI Colour, Hi PI Object	.11**
3	High PI Colour, Hi PI Object	.02	Low PI Colour, Low PI Object	.02

*p<.05. **p<.01.

Figure 1



.29
0-4000 Colour FR
.84
.60
0-4000 Object FR
.63
Forgetting Rate
.47
-.38
D1
.53
Object Speed
.69
Processing Speed
-.33
.80
Working Memory
.68
Object WM Span
.54
.38
Counting Speed
.79
-.41
.84
Counting WM Span
.30
-.42
.43
.54
Digit Span
.68
Storage Ability
.36
Word Span
.80

Appendix

Memory Stimuli used in the Object and Colour Forgetting Tasks

Pool A	Pool B
back	men
room	home
head	face
night	saw
door	play
girl	car
book	land
bed	line
road	cold
sound	drink
heat	arm
touch	fight
smile	ball
dress	shop
note	step
lunch	post
nose	rain
dog	camp
park	shape
ring	page
gun	bag
date	trip
bath	fruit
lift	coat
ship	shirt
salt	bird
pool	band
goal	knee
tape	coach
jump	soap